ENVIRONMENTAL IMPACT OF MANUFACTURING SOFTWOOD LUMBER IN NORTHEASTERN AND NORTH CENTRAL UNITED STATES[1]

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Abstract. Finding the environmental impact of building materials is becoming increasingly more important because of public environmental awareness. Accurate and precise life-cycle inventory data on wood products are needed to meet this demand. This study examined softwood lumber manufacturing in the northeastern and north central US using life-cycle inventory methods. Material flow, energy type, and energy use were identified for these sawmills. A softwood log mass conversion of 42.1% to planed dry lumber was found. Values of 355 MJ of electricity and 2730 MJ of processed energy per cubic meter were determined for manufacturing planed dry softwood lumber burning mostly green wood residues on-site for energy. Biomass and fossil carbon dioxide production of 187 and 65.1 kg/m^3, respectively, were estimated. Lowering energy consumption would be of great benefit to the mills, and thus society, in reducing the environmental burden, especially in sawing and drying.

Keywords: Life-cycle inventory, softwood lumber, LCI, green material, CORRIM, environmental impact.

INTRODUCTION

Softwood lumber from northeastern and north central (NE/NC) species is used primarily for framing lumber and as material for moulding manufacture depending on the species processed. Total annual softwood production for the US in 2006 was 89.0 Mm^3 (USCB 2008). Total annual softwood lumber production for the NE/NC region in both 2006 and 2007 was 4.37 Mm^3 (USCB 2008). Most softwood lumber is consumed domestically, but an estimated 2.06 Mm^3 was exported. Also, 53.3 Mm^3 was imported in 2006 (USCB 2008).

Domestic softwood lumber production occurs mostly in the Pacific Northwest and the southeast (SE) US. A smaller amount, roughly 5%, of softwood lumber production occurs in the NE/NC region. Most softwood lumber is used in residential construction, including new construction and repair and remodeling of existing buildings.

Economic costs, energy consumption, and environmental impact of residential building products are playing an increasingly important role because of increased public awareness of environmental issues related to the building industry. In 2003, the residential building industry used 87.6 Mm^3 of softwood lumber in the US (Spelter et al 2007). One major reason for this large volume in residential building is the increase in average building size. The average-sized single-family

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residential home has increased 25% from 193 m^3 in 1991 to 234 m^3 in 2007. Another factor was the doubling in number of single-family residential buildings constructed from 1991 to 2005. The latter reason now plays less of a factor because of a large drop in the current single-family residential construction seasonally adjusted annual rate from a high of 1.64 million units in 2005 to 0.668 million in November 2008 (USCB 2009).

Another new trend is "green building" that is expected to play an increasingly larger role in the residential building industry. Green building is the practice of improving energy efficiency for materials, construction, and operation while reducing the overall environmental impact of building. Two percent ($7.4 billion) of new residential starts in 2005 were classified as green buildings, and the minimum market share is expected to increase to 5% ($19 billion) by 2010 (MHC 2006; Murray 2008). Developing a sound policy for building practices, especially for green building, must be a priority if the US is to decrease its environmental burden on the world's resources. However, more scientific evidence is needed to evaluate claims for green building materials.

Accurate baseline life-cycle inventory (LCI) data are needed as part of this broader scientific approach for determining building styles, type of construction materials, and product improvements with a focus on reducing environmental burdens. This LCI study intends to provide useful data by examining the environmental impact of softwood lumber production in the NE/NC. In addition, these data can be interconnected into the scientific database managed by the National Renewable Energy Laboratory to complete a life-cycle analysis of softwood lumber-related wood products (NREL 2008).

LCI provides an accounting of energy and waste associated with the creation of a product through use and disposal. In this study, the gate-to-gate LCI tracks softwood lumber production from logs stored in the log yard to planed dry lumber leaving the sawmill. Life-cycle analysis (LCA) is a broader examination of the environmental and economic effects of a product at every stage of its existence from harvesting to disposal and beyond. Such an assessment is beyond the scope of this study. For this LCI study, tracking the material flow of softwood lumber is needed for an accurate survey of the different unit processes.

Material flow is tracked from raw material from logs to planed dry lumber, the final product. Rough green (freshly cut) lumber sawn from incoming softwood logs is typically dried in conventional dry kilns using wood and fossil fuels as heat sources. The sawing process consumes the highest percentage of electrical energy. Before drying the lumber, boards are stickered and stacked to aid drying and prevent drying defects. The drying process consumes roughly 70 – 80% of the total energy required for producing softwood lumber (Comstock 1975). Total energy includes both electrical and thermal. The rough dry lumber is planed to required dimensions after drying.

The goal of the present study is to document the LCI of planed dry lumber production from softwood logs and determine the material flow, energy use, and emissions for the softwood lumber manufacturing process on a per-unit basis for the NE/NC (Fig 1). Primary data were collected through questionnaires mailed to lumber mills, and secondary data were collected from peer-reviewed literature per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2001).

Several commercial softwood species are sawn in the NE/NC. Of the six mills surveyed in this region, five were in Maine and the other was in Michigan. Maine and Michigan are the two highest softwood lumber-producing states in this region. Greater participation from other states would have increased data representation. The Michigan mill produced red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*), and four of the five Maine mills produced eastern white pine (*Pinus strobus*). Balsam fir (*Abies balsamea*) and eastern spruce (mixture of red spruce [*Picea rubens*], black spruce [*Picea mariana*], and white spruce [*Picea glauca*]) were produced at the other Maine mill. The species breakdown for this
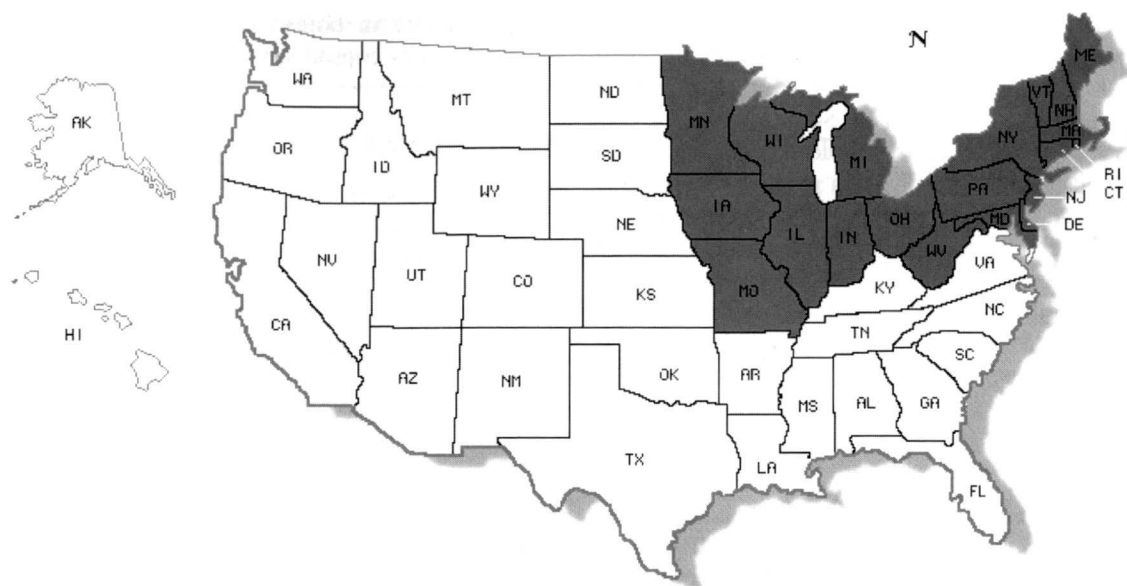
Figure 1.   The dark area is the region selected for life-cycle inventory of softwood lumber production in the northeastern and north central US.

region from surveyed data were as follows: 45% eastern white pine, 21% red pine, 2% jack pine, 5% balsam fir, and 27% eastern spruce (mix).

Material and energy balances were calculated from primary and secondary data sources. Using these material and energy values, the environmental impact was found from modeling emissions through SimaPro 7 software (Pré Consultants 2008), which follows ISO 14040 protocols. SimaPro was used in previous CORRIM-initiated LCI projects: hardwood lumber (Bergman and Bowe 2008), softwood lumber (Milota et al 2005), softwood plywood (Wilson and Sakimoto 2005), I-joist production (Wilson and Dancer 2005a), glue-laminated timbers (Puettmann and Wilson 2005), and laminated veneer lumber (Wilson and Dancer 2005b).

METHODOLOGY

Softwood Lumber Manufacturing and the Three Main Unit Processes

Producing softwood lumber involves three main unit processes—sawing, drying, and planing (Fig 2), with energy generation as an auxiliary
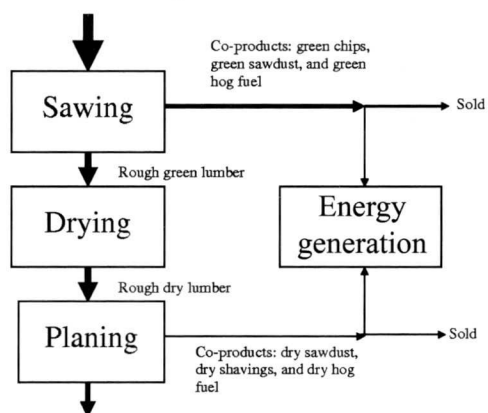
Figure 2.   Description of the three unit processes for softwood lumber manufacturing showing wood material flow through mill.

process. In the sawing process, incoming softwood logs (the raw material) are sawn into mostly 4/4 and 8/4 lumber of random width and mostly 2.4-m length. The sawing process uses the most electrical energy of all unit processes. Once the rough green lumber is tallied (to measure production volume) and stickered for

drying, the lumber is typically dried to 11 – 19% MC mostly using energy-intensive drying methods such as kiln drying. Final MC is dependent on final use of the lumber. Some air drying does occur. After drying is complete, rough dry lumber is planed to the dimension required for the final product. The energy generation process provides electricity and heat primarily produced on-site for these three processes. Coproducts are both sold and used for energy generation. In this LCI study, when referring to lumber and other coproducts, the term green is used in the context of freshly cut material that is roughly 50% water.

Sawing. Sawing begins with logs in the mill yard and ends with sawn rough green lumber and wood residue from the sawing process: bark, sawdust, slabs, edgings, and chips. Any combination of these materials is termed hog fuel. Most wood residue such as chips is sold as a coproduct, whereas the other residues, especially sawdust, are combusted as fuel for heat and power.

Drying. Drying begins with rough green lumber and ends with rough dry lumber bound for the planer mill. Drying produces most of the volatile organic compounds (VOCs) generated on-site and uses the most energy produced on-site from wood and fossil fuel combustion.

Auxiliary energy generation. This provides all on-site heat and some on-site electricity for the other three processes by burning wood, some oil, or a little propane. The outputs of this unit process are steam from boilers, electricity from cogeneration units, solid waste (wood ash), and air emissions (eg CO_2, CO, and particulate) from combustion.

Planing. Planing begins with stickered, rough kiln-dried lumber and produces surfaced and packaged lumber sorted by type, size, and grade as well as planer shavings, sawdust, and lumber trim ends (dry wood residue). Surveyed data accounted for lumber trim ends under shavings and sawdust therefore had no separate category. This process is the final stage of manufacturing. Some dry wood residue is combusted on-site in boilers for energy, although most is sold as coproducts.

Functional Unit

Material flows, energy use, and emission data are standardized to a per-unit volume basis for 1.0 m^3 of planed dry lumber, the final product of the softwood lumber manufacturing process. Allocating all material and energy in this manner standardizes the results to meet ISO protocols and can be used in other CORRIM studies, including LCA (CORRIM 2001; ISO 2006a, 2006b).

A direct conversion between cubic meters and 1000 board feet is 0.424 MBF/m^3 (2.36 m^3/MBF), which does not account for the nominal vs actual dimensions in BF measure. The US industry standard uses nominal dimensions, and commodity lumber is sold by variations of a thousand board feet (MBF). In this softwood LCI study, actual dimensions are used so that 1 m^3 equals 0.625 MBF (1.60 m^3/MBF). Also, the assumed dimensions used to convert board feet to cubic meters are the actual planed dimensions of 38 × 140 mm for the nominal dimensions of 50 × 150 mm with for a 2.4-m board with some trim end loss. Rough green lumber and rough dry lumber were assumed to be 2.08 and 1.96 m^3/MBF (FPL 1999a; Fonseca 2005; USDC 2005).

System Boundaries

Boundary selection is important because the material and energy that cross this boundary must be accounted for (Fig 3) through the gate-to-gate LCI. Two boundaries are defined by CORRIM (Wilson and Sakimoto 2005) and are used to track the environmental impact of softwood lumber production. One is the total (cumulative) system boundary (solid line in Fig 3), which includes both on- and off-site emissions for all consumed material and energy. The site system boundary (dotted line in Fig 3) is the environmental impact for emissions released only at the sawmill (on-site) from the three unit processes. Examples of off-site emissions are grid electricity
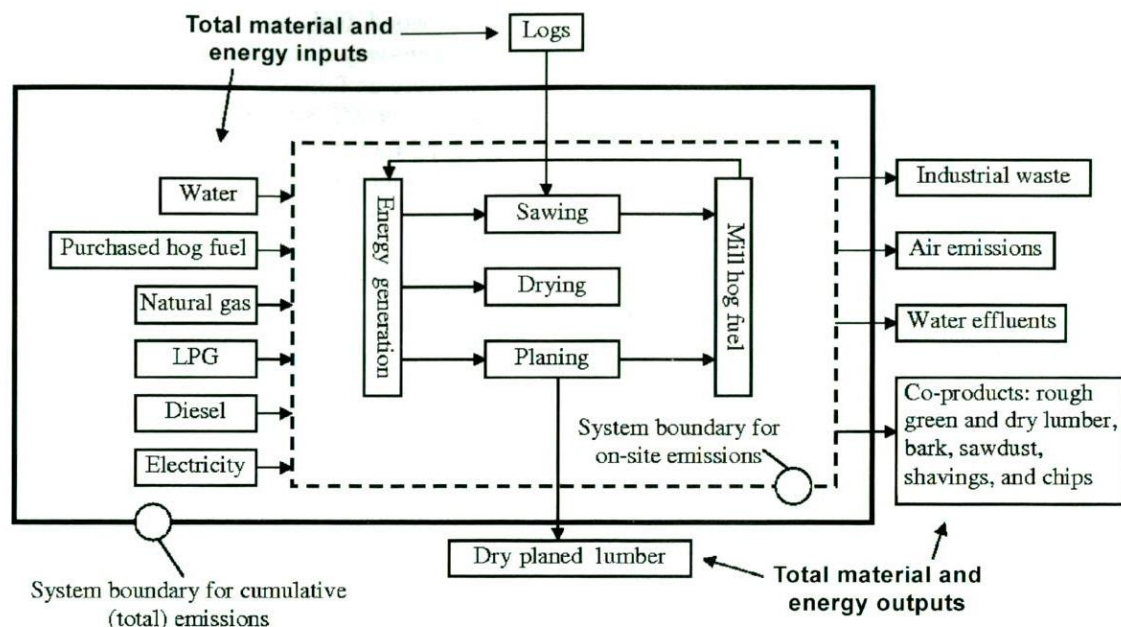
Figure 3.   System boundaries for softwood lumber production.

production, transportation of logs to the mill, and fuels produced off-site but used on-site. On-site emissions are from burning wood and fossil fuels in boilers and on-site transportation.

Assumptions

Bergman and Bowe (2009) provided detailed assumptions used to determine the results for this LCI study as defined in CORRIM Research Guidelines for Life Cycle Inventories (COR-RIM 2001).

RESULTS AND DISCUSSION

Material Flow

A rigorous material and energy balance was completed on primary mill data obtained from the six softwood mills located in the NE/NC. The survey data were modeled using SimaPro 7 to find the raw material and environmental impact allocated for 1 m^3 of planed dry lumber.

All energy and material values were weight-averaged from the six mills across 20 states in the NE/NC (Fig 3). The surveyed data spanned a 12-month period during 2006 and 2007. For the six mills, 531,000 m^3 rough green lumber was produced out of a total production from this region of 4.37 Mm^3. This value is roughly 12% (USCB 2008) of the total production for either 2006 or 2007. A minimum of 5% is required for data quality (CORRIM 2001). Also, 486,000 m^3 and 365,000 m^3 of rough dry lumber and planed dry lumber, respectively, were produced from this 531,000 m^3 of rough green lumber. Some rough green and rough dry lumber were sold.

Weight-averaged annual production for the surveyed softwood sawmills was 110,000 m^3 with a range of 46,800 – 169,000 m^3. A large production hardwood lumber mill is considered 30,800 m^3 or more (Bergman and Bowe 2008). Additional weight-averaged mill features were a log diameter of 239 mm with a range of 170 – 356 mm and production kiln capacity of 1420 m^3 with a range of 909 – 2120 m^3.

For the mass balance, this LCI study examined the three main unit processes and the overall process to track material flow. Using a weight-averaged approach and excluding bark, 931 oven-dried (OD) kg of incoming softwood logs

with a green-specific gravity of 0.361 produced 1.0 m^3 of planed dry lumber. Sawing produced 496 kg of rough green lumber; the drying process did not result in any loss of wood. Planing reduced the 496 OD kg of rough dry lumber to 392 OD kg of planed dry lumber for a roughly 20% reduction in mass. The boiler burned 68 OD kg of both green and dry wood fuel produced on-site (Table 1). Also, pulp chips were the largest wood residue produced at 348 OD kg/m^3 planed dry lumber, roughly 37% of incoming wood mass. Overall, the log was reduced to 42.1% of its original mass by converting it to the final product of planed dry lumber. A 1% difference was calculated based on the overall mass balance that included intermediate products such as rough green and rough dry lumber.

Mills are concerned with their lumber recovery factor. Therefore, the volume reduction was determined. Most mills in the US use nominal volumetric values such as board feet to purchase and sell their products. Shrinkage during drying was considered. In the NE/NC region, 2.58 m^3 of softwood logs is sawn into 1.30 m^3 of rough green lumber dried to 1.23 m^3 of rough dry lumber. Planing the rough dry lumber produces 1.0 m^3 of planed dry lumber for a total volume conversion of 38.8% from incoming logs.

Regarding transportation of material (resources) to the mill, the environmental burdens were not included in environmental impact analysis. These resources included logs, bark on logs,

purchased wood fuel, and all deliveries made by truck. One-way distances and MC for these materials were as follows: 109 km for logs and bark, both at 96.5% MC, and 58.8 km for purchased wood fuel at 80.2% MC. All trucks were considered empty on return.

Energy Consumption

Softwood lumber uses both electrical and thermal energy in the manufacturing stage. Most of the electricity used on-site is produced off-site. Electrical energy is required by all three unit processes with the majority consumed in the sawing process. Total electrical consumption of 355 MJ/m^3 planed dry lumber was determined. Based on the following percentages of 54.7, 25.5, and 19.8% for the sawing, drying, and planing processes, these processes consumed 194, 90.5, and 70.4 MJ/m^3, respectively. This includes both off-site and on-site (wood-fueled cogeneration) electrical sources (Table 2). Wood-fueled cogeneration provided 14.3% of this total electricity consumed. As for total process energy consumption, a higher amount of overall energy is contributed to thermal energy.

Producing planed dry softwood lumber from mill gate logs requires 2.7 GJ/m^3 of processed heat (thermal energy). All the thermal energy used on-site was produced on-site and was used for drying lumber, plant heating, and cogeneration. For softwood lumber, weight-averaged total

Table 1. *Weight-averaged wood mass balance for 1.0 m^3 of planed dry lumber (oven dry kg).*

Material (oven-dried kg)[a]	Sawing process		Boiler process	Drying process		Planer process		All processes combined		
	Input	Output	Input	Input	Output	Input	Output	Input	Output	Difference
Green logs	931							931	0	−931
Green chips		348						0	348	348
Green sawdust		84	42					42	84	42
Green bark[b]	127	127						127	127	0
Green hog fuel		3	3					3	3	0
Rough green lumber		496		496				496	496	0
Rough dry lumber					496	496		496	496	0
Planed dry lumber							392	0	392	392
Dry shavings			13				94	13	94	81
Dry mixings			10				10	10	10	0
Sum	1058	1058	68	484	484	484	484	2118	2050	−68

[a] Values given in oven-dry weights.
[b] Bark volume is not included in log scale.

Table 2. *Material and energy consumed on-site to produce a cubic meter of planed dry lumber (SimaPro input values).*

Fuel type	Quantity	Units[e] (m^3)
Fossil fuel[a]		
Fuel oil #1	0.04	L
Fuel oil #2	8.91	L
Electricity[b]		
Off-site generation	304	MJ
On-site generation	51	MJ
On-site transportation fuel[c]		
Off-road diesel	2.04	L
Gasoline	0.038	L
Renewable fuel[d]		
On-site wood fuel	68.1	kg
Purchased wood fuel	45.8	kg
Water use		
Surface water	811	L
Ground water	172	L

[a] Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas, 43.3 for fuel oil #1 and #2, 45.5 for fuel oil #6, and 54.0 for propane.
[b] Conversion unit for electricity is 3.6 MJ/kWh.
[c] Energy values were determined using their higher heating values in MJ/kg: 45.5 for off-road diesel and 54.4 for gasoline.
[d] Values given in oven-dried weights (20.9 MJ/OD kg).
[e] 1.60 actual m^3 per 1.0 thousand board feet (MBF) planed dry lumber.

processed energy of 2730 MJ/m^3 of planed dry lumber was found from higher heating values with 2020 MJ for drying, 488 MJ for on-site electrical generation (cogeneration), and 224 MJ for plant heat. Lowering overall energy consumption could be done by upgrading or overhauling existing older and inefficient dry kiln facilities. Installing progressive dry kilns commonly used in Scandinavian countries would also significantly reduce energy consumption. In addition, other drying methods can be used depending on species, fuel costs, and wood residue use. Air drying lumber is one such method. Electrical energy consumption of 355 MJ/m^3 of planed dry lumber was also determined. Of the total electricity, grid electricity and on-site (cogeneration) electricity provided 304 and 51 MJ, respectively. Using improved sawing practices such as the Best Opening Face program (Harpole and Hallock 1977) and thinner saw kerfs have increased lumber yields while lowering electricity consumption. Cogeneration electrical efficiency was estimated at 10.5%, a lower-than-expected value. Process energy con-

sumption varied considerably depending if the mill ran a cogeneration unit. One mill that produced its own electrical power consumed over three times the amount of wood residues per-unit volume of lumber dried than mills that did not produce their electrical power.

Wood residues from wood manufacturing facilities are typically burned on-site for generating thermal energy, and softwood lumber is manufactured in one such type of facility. In this study, wood fuel derived from the sawing and planing process, 68.1 OD kg, and some purchased (off-site) wood fuel, 45.8 OD kg, were burned on-site in boilers. These wood fuels comprised 87% of the fuel burned on-site with No. 2 fuel oil comprising the remaining portion. No. 1 fuel oil played a minor role compared with wood and No. 2 fuel oil. For off-site (beyond the mill's boundaries) consumption, coal was the largest energy resource consumed because most grid electricity is from coal power plants located in the NE/NC. Coal also releases more anthropogenic CO_2/kWh generated than other fossil fuels such as natural gas because of lower electrical conversion efficiencies.

The location of the softwood lumber facility affects the environmental impact because most electricity used is from the electric power industry. For example, the Pacific Northwest region produces most of their electricity from hydroelectric sources, but the SE region is similar to the NE/NC where coal power is the largest source (Milota et al 2005). This difference in geographical location determines the composition of grid electricity provided to the mill. An average composition of (off-site) electrical generation was found for the NE/NC by totaling the amount of the different fuel sources for each of the 20 states given in 1000 kWh and calculating the percentages (USDOE 2007). The most significant electric power contributor in this region is coal with 58.5% of total electrical utility power being provided by this fuel source. Other fuel sources are nuclear, natural gas, petroleum, hydroelectric, and renewables, which provide 24.9, 11.0, 1.2, 2.5, and 1.9%, respectively.

On-site transportation of wood stock is a major fuel consumer with off-road diesel having the highest consumption. Off-road diesel and gasoline are also used for trucks, forklifts, front-end loaders, and other equipment used within the site system boundary of the facility. Off-road diesel consumption was 2.04 L/m^3 of planed dry lumber and was consumed at 60 times the rate of gasoline. Propane consumption was insignificant compared with either off-road diesel or gasoline. On-site transportation fuel consumption is broken down for the unit processes into the following percentages: 60, 20, and 20% for sawing, drying, and planing, respectively. The corresponding values of the three processes for off-road diesel were 1.22, 0.41, and 0.41 L, and for gasoline, 0.0228, 0.0076, and 0.0076 L, respectively.

Total energy consumption per cubic meter of planed dry softwood lumber was found to be comparable to published data (Comstock 1975; Breiner et al 1987; Armstrong and Brock 1989). However, unlike previous studies, this study examined processes such as facility heating and cogeneration because the energy use of these processes was significant. Most facilities use kiln-drying to remove water from lumber; however, air drying is an alternative drying method. Air drying lumber provides the lowest energy use of all drying methods but has the least control, resulting in the highest level of degrade (FPL 1999b; Denig et al 2000; Nebel et al 2006).

Environmental Impact

Material and energy resources consumed to manufacture 1 m^3 of planed dry softwood lumber are shown in Table 2. These LCI input values are unallocated and were inputted into SimaPro 7 to find the environmental burdens of manufacturing 1 m^3 of planed dry softwood lumber. Table 3 gives on-site energy values unallocated and allocated to the planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 2 and were the sum of all fuel and electricity inputs to the process. Allocated on-site energy

Table 3. *Fuel and electrical energy used on-site to produce a cubic meter of planed dry lumber.*

	Energy use at mill	
	Unallocated (MJ/m^3)	Allocated (MJ/m^3)
Fossil fuel[a]		
Fuel oil #1	1.61E+00	1.15E+00
Fuel oil #2	3.45E+02	2.47E+02
Electricity[b]		
Off-site generation	3.04E+02	2.17E+02
On-site generation	5.10E+01	3.64E+01
On-site transportation fuel[c]		
Off-road diesel	7.89E+01	3.05E+01
Gasoline	1.32E+00	5.11E-01
Renewable fuel[d]		
On-site wood fuel	1.42E+03	1.02E+03
Purchased wood fuel	9.57E+02	6.83E+02
Total	3.16E+03	2.23E+03

[a] Energy values were determined using their higher heating values in MJ/kg: 43.3 for fuel oil #1 and #2.
[b] Conversion unit for electricity is 3.6 MJ/kWh.
[c] Energy values were determined using their higher heating values in MJ/kg: 45.5 for off-road diesel and 54.4 for gasoline.
[d] Values given in oven-dried weights (20.9 MJ/OD kg).

use is roughly 71% of the total unallocated on-site use. Material and energy consumed at the mill for SimaPro 7 gave LCI outputs allocated to manufacturing dry planed lumber only, not to associated wood coproducts. Some LCI outputs listed raw materials used.

Major uses of raw material, outside of logs processed into lumber, were purchased wood fuel (waste), coal, crude oil, and limestone with allocated values of 32.7, 15.3, 8.52, and 4.93 kg, respectively. A wood volume of 1.23 m^3 entered the planing process to produce 1.0 m^3 planed dry lumber (Table 4). Limestone is used to remove sulfur dioxide produced from burning coal. Limestone and most of the coal were used to produce off-site electricity, and oil was used for both off-site electricity and on-site thermal energy.

Life-Cycle Inventory

Two different LCI scenarios for manufacturing softwood lumber were evaluated: allocated cumulative and allocated site. The allocated cumulative scheme examined all emissions for electricity and thermal energy generation that were required to produce 1.0 m^3 of planed dry

Table 4. *Raw materials consumed during production of planed (surfaced) dry lumber: cumulative, allocated gate-to-gate life-cycle inventory values (SimaPro output values).*

Raw material[d]	Quantity[a]	Units/m^3
Logs at mill gate[b]	1.23	m^3
Water, well, in ground[e]	0.072	m^3
Water, process and cooling, surface[e]	0.341	m^3
Purchased wood waste	32.7	kg
Coal, in ground[e]	15.3	kg
Gas, natural, in ground[e]	2.08	kg
Oil, crude, in ground[e]	8.52	kg
Limestone, in ground[e]	4.93	kg
Energy, from hydroelectric power[c]	4.74	MJ
Energy, unspecified[c]	3.28	MJ
Uranium, in ground[e]	0.000425	kg

[a] Energy values were found using their higher heating values in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.
[b] Amount of wood in lumber form entering the planing process; no shrinkage taken into account from drying process.
[c] Conversion units for electricity is 3.6 MJ/kWh.
[d] Values are allocated and cumulative.
[e] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

lumber starting with softwood logs at the mill gate. These emissions involve the cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels, and purchased wood fuel used in the boiler and fossil fuels used in yard equipment such as forklifts. Also, emission data for on-site combustions of the two latter materials and wood fuel generated on-site were included. Transportation of logs to the mill gate was not included in this scenario. Allocated site scheme includes only emissions from combustion of all fuels used at the mill and therefore does not involve manufacturing and delivery of material and electricity consumed at the mill.

Table 5 shows the lower environmental impact of site compared with cumulative emissions allocated to manufacturing softwood lumber. Particulates and carbon dioxide are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. Wood and coal combustion efficiency are typically measured by the amount of particulate emitted. Cumulative and site particulate matter (PM) 10 levels were 0.0291 and 0.0215 kg/m^3. The PM 10 contributions to burning coal for generating electricity were not accounted for in the site emission scenario.

Table 5. *Life-cycle inventory results for total emissions on a per-unit basis of planed dry lumber.*

Substance	Allocated cumulative (kg/m^3)	Allocated site (kg/m^3)
Water emissions		
Biological oxygen demand (BOD)	2.35E-04	—
Cl$^-$	5.74E-03	1.09E-06
Suspended solids	2.58E-02	2.09E-04
Oils	2.42E-03	—
Dissolved solids	1.30E-01	—
Chemical oxygen demand (COD)	2.25E-03	—
Soil emissions		
Waste in inert landfill	0.22	0.22
Waste to recycling	0.018	0.018
Solid waste	15.2	8.00
Air emissions		
Acetaldehyde	2.67E-04	2.67E-04
Acrolein	5.48E-07	—
Benzene	3.20E-04	3.20E-04
CO	1.27	1.24
CO$_2$ (biomass)	187	187
CO$_2$ (fossil)	65.1	25.1
CH$_4$	8.62E-02	7.60E-05
Formaldehyde	1.60E-03	1.59E-03
Mercury	1.28E-06	3.35E-07
NMVOC[a]	4.02E-01	2.19E-01
NOx	7.98E-02	5.95E-03
Particulate (PM10)	2.91E-02	2.15E-02
Particulate (unspecified)	4.01E-02	—
Phenol	3.55E-03	3.55E-03
SOx	3.62E-01	5.65E-02
VOC	6.52E-01	6.52E-01

[a] NMVOC is nonmethane volatile organic compounds.

Carbon dioxide (CO$_2$) emissions are separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Biogenic CO$_2$ may be considered carbon-neutral because the CO$_2$ emitted is reabsorbed during the growth of the tree and released on decomposition or burning of the tree. However, the process of burning wood fuel for energy uses nonrenewable fuel sources during transportation and harvesting of logs that is not compensated for in the carbon balance. Cumulative emission values of 187 and 65.1 kg were reported from SimaPro for CO$_2$ (biogenic) and CO$_2$ (anthropogenic), respectively, and site emission values of 187 and 25.1 kg for the same. The proportion of biogenic CO$_2$ to total CO$_2$ increased from 74.1 – 88.1% from

the cumulative to site schemes. A lower anthropogenic CO_2 for site emissions indicates mainly the effect that grid electricity has on CO_2 emissions. VOC gases produced mostly from drying lumber generated the same value of 0.652 kg regardless of scenario. An overall literature value of 0.752 kg/m^3 was calculated (Rice and Erich 2006; Rice 2008).

The SE is a primary region for softwood lumber production. Our LCI study and two previous softwood and hardwood lumber LCI studies (Table 6) indicated that less electrical and process energy was used than in manufacturing hardwood lumber in the NE/NC and softwood lumber than in the SE (Milota et al 2005; Bergman and Bowe 2008). Total energy consumption was 30% less for NE/NC than SE softwood lumber manufacturing, although the NE/NC process used more energy to keep the facility heated during winter months than did the SE process. One reason for the difference in overall energy consumption is the lower density of softwoods manufactured in NE/NC compared with SE.

Carbon Balance

Carbon tracking plays an increasingly significant role in policy decision-making in the US and the world. Using a mixture of softwood roundwood values for the NE/NC, the impact of carbon was determined by estimating values of carbon found in wood and bark as described from previous studies such as Skog and Nicholson (1998). Carbon input was 543 kg/m^3 planed dry lumber with the following carbon sources in kg: 432 from

logs, 59 from bark, and 53 from wood fuel. The total carbon output was 549 kg/unit basis with the following carbon sources in kg: 182 from planed dry lumber, 309 from coproducts, 7 from solid emissions, and 52 from air emissions. Anthropogenic carbon dioxide was assumed to be derived from burning fossil fuels and therefore not included in the carbon balance. This resulted in a percentage difference of 1.1% between the total carbon input and output. For a full description of carbon content in air emissions from compounds such as biogenic carbon dioxide, methane, and carbon monoxide, see Bergman and Bowe (2009).

CONCLUSIONS

Lowering energy consumption would be of great benefit to the mills both in terms of financial benefits (cost reduction) and environmental burden benefits, especially in sawing and drying. There are several approaches to lowering energy consumption, and mills that incorporate these methods would ultimately have significantly lower energy use and thus less environmental burdens.

Drying consumes the highest proportion of fuel. In this study, wood fuel accounts for 87% of thermal energy used. Lowering overall energy consumption in drying is necessary and has a large influence on reducing the environmental impact on softwood lumber manufacturing. All of the following would aid in this endeavor: replacing dry kilns with progressive kilns, refurbishing inefficient dry kilns, and more air drying of lumber. Although one mill did have an air yard, air drying has not been the preferred method because air drying degrades lumber, and large quantities of drying stock are required. Drying degrade is a loss in lumber quality caused by drying; greater control of the drying process typically reduces drying degrade. Maintaining a large lumber inventory for air drying reduces profits because of delays in recovery investments. However, increasing the use of air drying, or air drying before kiln drying, especially for species for which color is not a problem, would lower the amount of energy required for

Table 6. *Comparison of lumber energy use.*

	Overall energy consumption[a]	
	Electrical energy (MJ/m³)	Process energy (MJ/m³)
NE/NC softwood lumber[b]	355	2730
NE/NC hardwood lumber[c]	597	5500
SE softwood lumber[d]	335	3560

[a] All values per unit of planed dry lumber; unallocated energy use at mill.
[b] 1.60 m³ per 1.0 MBF (thousand board feet) planed dry lumber.
[c] 1.76 m³ per 1.0 MBF planed dry lumber and includes walnut steaming and plant heating.
[d] 1.623 m³ per 1.0 MBF planed dry lumber; 3.6 MJ per kWh, 1054 MJ per million BTU.

the drying process. Material used for construction lumber but not for moulding products would benefit from this approach. Therefore, improving air drying methods would lower energy use while maintaining lumber quality and reducing the environmental impact of softwood lumber.

Sawing consumes the highest proportion of electricity in the manufacturing of softwood lumber. Thus, installing optimization equipment would lower electrical consumption by reducing sawing errors. Thinner kerf saws reduce electrical consumption and also reduce the volume of green wood residue produced.

The region selected for production affects the environmental impact of this product because coal is the off-site material used most for electrical power generation in the NE/NC region. Most power in the Pacific Northwest is produced from hydroelectric and natural gas, whereas most power in the SE is produced from coal and uranium (like in the NE/NC region). Transferring more softwood lumber production to the Pacific Northwest would reduce anthropogenic carbon dioxide emissions.

ACKNOWLEDGMENTS

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